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*InfraCAM*TM: A Hand-Held Commercial Infrared Camera Modified for Spaceborne Applications

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***InfraCAM™*: a hand-held commercial infrared camera modified for spaceborne applications**

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ABSTRACT

In 1994, Inframetrics introduced the *InfraCAM™*, a high resolution hand-held thermal imager. As the world's smallest, lightest and lowest power PtSi based infrared camera, the *InfraCAM* is ideal for a wide range of industrial, non destructive testing, surveillance and scientific applications. In addition to numerous commercial applications, the light weight and low power consumption of the *InfraCAM* make it extremely valuable for adaptation to space borne applications.

Consequently, the *InfraCAM* has been selected by NASA Lewis Research Center (LeRC) in Cleveland, OH, for use as part of the DARTFire (Diffusive and Radiative Transport in Fires) space borne experiment. In this experiment, a solid fuel is ignited in a low gravity environment. The combustion period is recorded by both visible and infrared cameras. The infrared camera measures the emission from polymethyl methacrylate, (PMMA) and combustion products in six distinct narrow spectral bands.

Four cameras successfully completed all qualification tests at Inframetrics and at NASA Lewis. They are presently being used for ground based testing in preparation for space flight in the fall of 1995.

Keywords: handheld thermal imager, DARTFire experiment, PMMA combustion

1. INTRODUCTION

With the introduction of the Inframetrics *InfraCAM*, a new standard is established for small, lightweight, low power, hand-held, high sensitivity, high resolution thermal imaging systems. A unique design approach to video processing as well as the compact and efficient Inframetrics' patented Stirling cycle microcooler allow the unit to require less than 5 watts of power during operation. The extremely small size, low power, and light weight of the *InfraCAM* make it highly desirable for space borne applications.

One such application is the DARTFire combustion experiment,(DARTFire Science Requirements Documents) sponsored by the Microgravity Science and Applications Division at NASA headquarters and administered by NASA Lewis Research Center (LeRC) in Cleveland, OH. The DARTFire experiment is intended to gather radiometric emission data from the combustion of PMMA in a weightless environment. The purpose of this data is to increase the fundamental understanding of the mechanisms that cause flames to spread over solid fuels. This data has clear applications to fire safety.

In this experiment a small sample of PMMA is ignited. During the burn time, approximately 60 seconds, the infrared camera records the combustion process. A filter wheel constantly rotating in sync with the frame rate is fitted to the camera. The wheel rotates such that one of six different bandpass filters is placed in front of the camera sequentially. The image data can be sorted at a later date such that six sets of continuous spectral data result, one set from each

single bandpass filter. This paper presents the design of the commercial *InfraCAM*, the modifications performed for this application, a description of the experiment and the results of ground based testing.

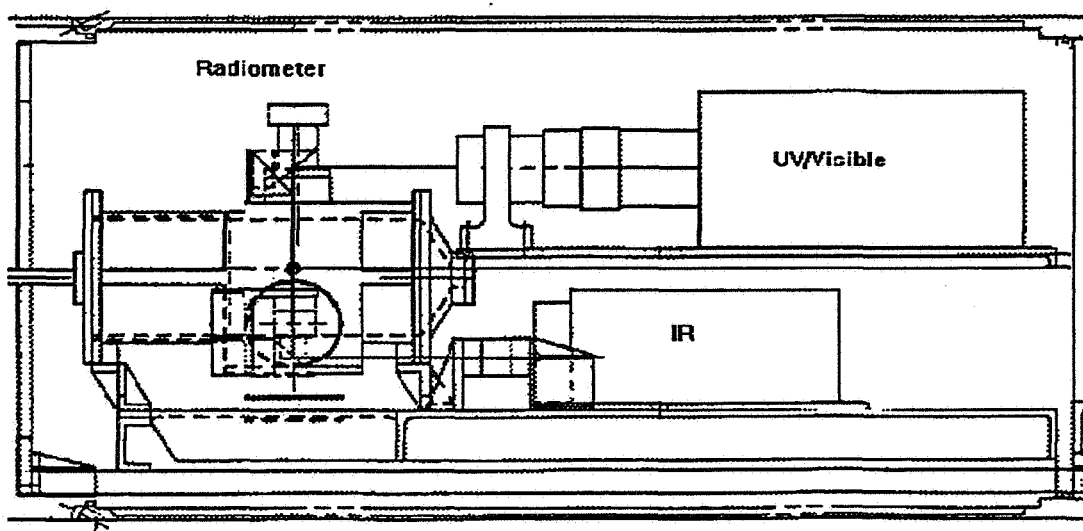


Figure 1: The experiment layout

2. WHY THE EXPERIMENT?

Flame spread is fundamentally different in microgravity due to the lack of buoyant flow that introduces the oxidizer into the combustion process and removes combustion products. Consequently radiation and diffusion dominate the process, making flame robustness highly sensitive to small changes in the environment. Radiative losses can extinguish the flame and small convections can greatly enhance the flame spread rate.

The sample to be subjected to combustion consists of black cast PMMA sheet stock of dimensions 2.0 cm long by 0.635 cm wide by 2.0 cm thick. Two samples will be ignited simultaneously in two different test sections. The thermal and flow environment of the samples is controlled to meet certain scientific requirements.

The overall objectives of the DARTFire experiment are to uncover the underlying physics and increase the fundamental understanding of the mechanisms that cause flames to propagate over solid fuels against a low velocity of oxidizer flow in the low-gravity environment that is found in spacecraft. Although the work is fundamental in nature, it has clear applications to fire safety in space and on earth. Specific objectives are as follows:

1. To analyze experimentally observed steady flame shape, measure gas-phase field variables, spread rates, radiative characteristics, and solid-phase regression rate for comparison with theoretical predictions.
2. To investigate the transition from ignition to either steady flame propagation or extinction in order to determine the characteristics of those environments that lead to flame evolution.

In order to meet these objectives, several types of data will be gathered during the experiment: infrared imaging, UV/visible imaging, temperature, pressure, radiation, velocity, acceleration levels, ignitor power, and flow rate.

3. SPECIES-SPECIFIC INFRARED IMAGING

The purpose of an infrared imager for these experiments is to obtain information regarding mass transport in the flame zone. An intensity contour corresponds to a combined temperature/species concentration field, and

numerical modeling is able to predict these intensities using computed temperature and species fields. An independent measure of the temperature field is obtained via thermocouple, so the infrared imaging provides a useful way of recording the species field for comparison with model predictions. The comparison will determine the validity of the Lewis number and mass diffusivity assumptions, or point out the need for improvement, to better capture the physics of the low-gravity flame spread process.

An infrared camera with narrow bandpass filters corresponding to CO₂ (4240 nm center wavelength, 25 nm bandwidth), H₂O (1870 nm center wavelength, 100 nm bandwidth), CO (4800 nm center wavelength, 100 nm bandwidth), soot (1600 nm center wavelength, 25 nm bandwidth), MMA vapor (3400 nm center wavelength, 400 nm bandwidth), and soot (3800 nm center wavelength, 25 nm bandwidth) radiation will be used to obtain species-specific radiation levels for comparison with model predictions. The bandwidth of each filter will be finalized based on ground testing. The field of view will be restricted to 3 cm along the sample length and approximately 2 cm above the sample. Measurements will be made during the entire test. Besides the spectral characteristic of the IR imager, its compact size, low weight, low power consumption, the capability of surviving in high G loads during launch, and landing, and computer interface, are features which made the Inframetrics *InfraCAM* IR imager the best candidate available on the market to meet the scientific and engineering objectives of the DARTFire project.

4. RELATIONSHIP TO OTHER PROGRAMS

DARTFire is one of a number of flight and ground experiments developed at NASA LeRC in cooperation with the scientific and technical community, aerospace industry, and government agencies and national laboratories. These experiments study microgravity science in the disciplines of fluid physics, materials science, and combustion science. DARTFire, like the Solid Surface Combustion Experiment, Spread Across Liquids, (SAL), Microgravity Smoldering Combustion, Transitional/Turbulent Gas-Jet Diffusion Flames, Combustion Module 1, and Droplet Combustion Experiment, study combustion in a space microgravity environment. DARTFire, like SAL, uses a sounding rocket vehicle. This suborbital vehicle provides a short duration microgravity environment, a maximum of 6 minutes at 10E-4Gs. This is considerably longer than the duration obtainable in drop towers, (3-5 seconds), and in aircraft, (approximately 20 seconds), greatly facilitating the science while minimizing the cost. The cost trade off of using an expendable launch vehicle (ELV) over the space shuttle is in reliability. An ELV is less reliable and the launch environment is more severe than the space shuttle.

The microgravity environment of space provides unique opportunities to study physical processes which cannot be investigated on earth due to the effects of normal gravity, such as the studies of the physics of flame spreading across solid-fuel surfaces. Initial studies of flame spreading have been accomplished as part of the Solid Surface Combustion Experiment /Polymethyl Methacrylate (SSCE/PMMA) program. The SSCE/PMMA program has been successful and has acquired meaningful data for flame spread across solid fuels (paper and PMMA) in a quiescent environment (no oxidizer flow). In order to expand the state of knowledge of how flames spread, it is necessary to introduce additional variables which cannot be studied using the SSCE/PMMA hardware set. These variables are oxidizer flow and radiant heat flux. The DARTFire experiment will take the existing knowledge base and expand it to include the effects of these additional variables. In addition to studying the effects of these additional variables, the DARTFire experiment will include instrumentation not in the original SSCE/PMMA hardware set, including means of visually recording two-dimensional flame temperature contours and combustion products species emissions. As with the previous experiments, the microgravity environment of space currently provides the only means of studying the basic phenomenon of flame spreading over solid-fuel surfaces, due to the need for environmental conditions of 10E-4Gs or better for duration on the order of a few minutes. The expansion of basic scientific knowledge about the physics of flame spreading has significant potential applications to fire safety on earth and in space.

The DARTFire experiment is based on a proposal by Principal Investigator Robert A. Altenkirch of the University of Mississippi and Co-Investigators Sandra Olson of NASA Lewis Research Center and Subrata Bhattacharjee of San Diego State University. Like its predecessor (SSCE/PMMA), the experiment was originally conceived as a Shuttle mid-deck experiment. However, due to size, weight, and safety considerations, the experiment design has

been reconfigured for flight on a sounding rocket. A primary objective is to develop the DARTFire experiment as a minimum cost payload. The current plan calls for a total of three sounding rocket flights to be performed.

5. DATA REGARDING FLIGHT LOGISTICS

The experiment will be developed by the Space Experiments Division of NASA LeRC as a sounding rocket payload (Terrier-Black Brant) to be launched from the White Sands Missile Range (WSMR) (See figure 2). The payload portion of the rocket consists of the DARTFire experiment section developed by NASA LeRC, plus additional standard rocket sections supplied by Wallops Flight Facility, (WFF). These sections include the ignitor/separator, telemetry, S-19 boost guidance, and ORSA (parachute recovery) sections.

Following final checkout on the launch pad at WSMR, the experiment will be launched and automatically initiated by an electronic timer contained within the WFF supplied portion of the rocket. The rocket will utilize an S-19 boost guidance system which operates during the first few seconds of flight to stabilize the trajectory. The rocket is spin stabilized to minimize errors in its trajectory. After the rocket has reached approximately 100 km altitude, and has been de-spun via the yo-yo mechanism and cold-gas rate control system, the experiment will be powered up. The experiment will be controlled entirely by the on-board experiment computer. The computer will automatically execute the proper sequence of activities when power is applied to it by the telemetry section. An exception is the IR camera which, due to cool-down time requirements, will be configured to operate in standby mode during launch. The experiment will not be commanded from the ground. Operation of the rocket and its payload will remain the responsibility of WSMR personnel. LeRC personnel may, however, review downlink telemetry data showing performance of the rocket and power system, although no experiment data will be downlinked. Upon reaching the appropriate altitude, the experiment will undergo approximately 30 seconds of preparations before combustion of the two samples is initiated. Following ignition, thermocouple, radiometer, and imagery data will be collected for up to six minutes of microgravity time. This data will be stored on-board in the experiment computer and on dual video tape recorders. Near the end of the microgravity period, the samples will be extinguished and the oxidizer bottles drained by venting to space. The experiment will then be powered down. At the appropriate time, portions of the rocket will again spin-up the payload to four revolutions per second. At approximately 50,000 feet, the ORSA parachute will be deployed. The payload will land in the target area of WSMR and will be recovered by helicopter.

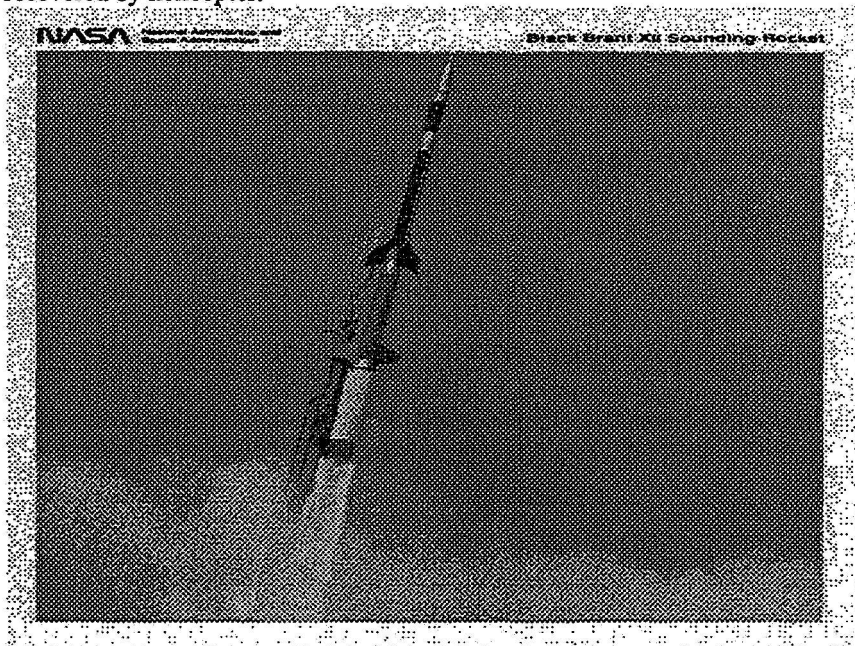


Figure 2: Black Brant XII Sounding Rocket

6. MAJOR COMPONENTS OF THE INFRACAM

Figure 3 shows a block diagram of the major subsystems of the commercially available *InfraCAM* prior to modification for the DARTFire experiment. The Integrated Dewar/Detector Assembly (IDA) consists of the integrated microcooler and vacuum sealed dewar. The key components of the dewar are the detector, which is mounted to the cold finger of the microcooler, cold shield and cold filter. Three printed circuit boards are used in the modular *InfraCAM* design. The focal plane interface PCB performs clock signal conditioning and creates the bias voltages required by the detector. This board can be easily replaced to accommodate other focal plane arrays. The power supply board drives the cooler motor, maintains the detector temperature, and converts the input battery power to the voltages required within the camera. The video processor board, described in greater detail later, conditions the video from the detector and creates TV compatible video.

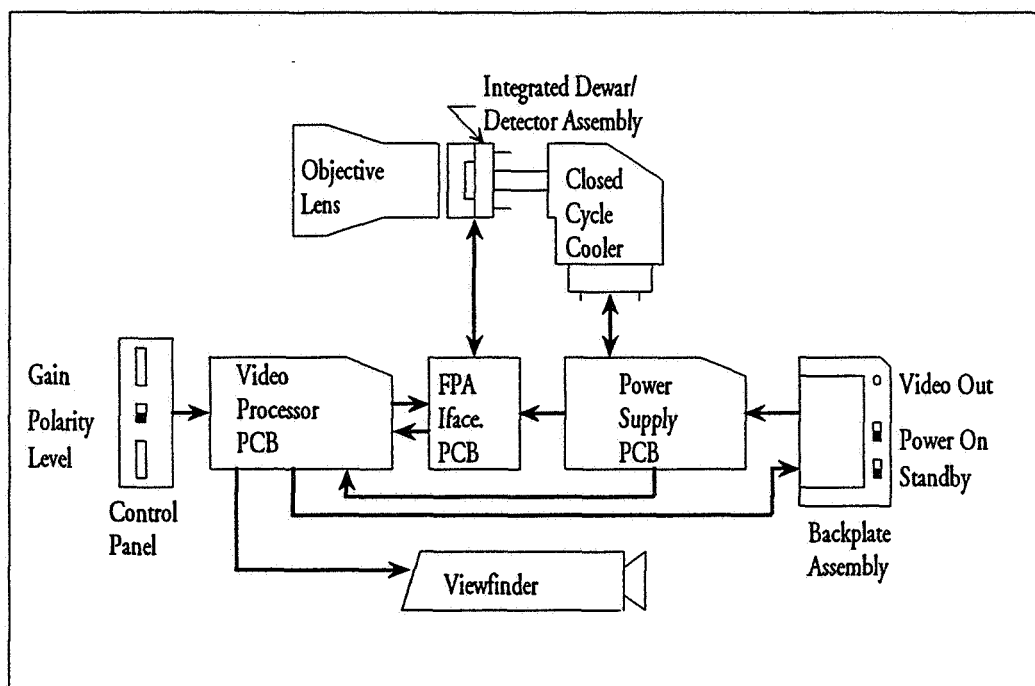


Figure 3: Block Diagram of the *InfraCAM*

The user interface consists of a level (brightness), gain (contrast) and polarity controls located on the front control panel. Additionally, two switches are located on the back of the unit to switch the power on and to place the unit into a standby operating mode if desired. Finally, a video output jack is located on the back plate for connection to a VCR and/or an external monitor. Figure 4 shows a cross sectional view of the *InfraCAM*.

The standard *InfraCAM* optical system is f/1.25. A cooled optical filter in the cold shield limits the spectral band to 3.4 to 5.0 microns. The optical system is designed for 100% cold shield efficiency. There are currently five lenses available for the *InfraCAM*. Four lenses have fixed focal lengths and one is a zoom telescope. The base unit comes with a 50 mm objective lens which provides an 8° field of view with an instantaneous field of view of 0.6 mrad. The three additional fixed focal length lenses, a 12.5 mm, a 25 mm and a 100 mm, offer a 32°, 16° and a 4° field of view with instantaneous fields of view of 2.50 mrad, 1.25 mrad and 0.3 mrad respectively. A 25 mm to 95 mm zoom telescope is available.

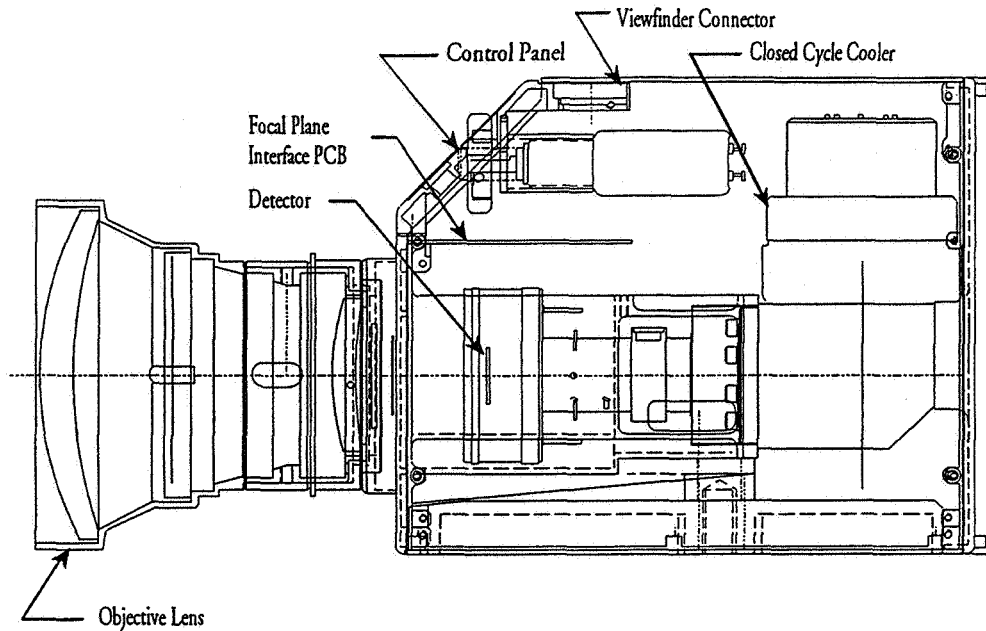


Figure 4: Cross Sectional View of the *InfraCAM*

The *InfraCAM* is designed around a 256 x 256 platinum silicide (PtSi) detector. Table 1 lists the key detector features. The FPA is integrated into a vacuum dewar assembly and cooled to cryogenic temperature (75° K) by the microcooler.

Table 1: PtSi Detector Key Features

Array Size	256 columns x 256 rows = 65,536 pixels
Architecture	X-Y Scan, Non interlaced
Pixel Size	30 μ m x 30 μ m
Optical Fill Factor	>87%
Spectral Sensitivity	1 - 5.7 μ m
"Dead" Rows or Columns	0
Operability	> 99.9%

The platinum silicide focal plane array is a hybrid construction. A PtSi detector array is indium bump bonded to a silicon multiplexer. The bump-bond electrically connects each detector with its own amplifier on the multiplexer. During readout, each of the 256 rows of the device are sequentially accessed. The multiplexer reads out all 256 pixels from the selected row. The integration time for each detector is the same, but skewed in time with respect to each other (rolling integration).

Due to the inherent stability of the PtSi detector (no drift in response or offset with time), the tight temperature regulation of the cooler drive electronics as well as the stability and repeatability of the correction circuitry, the *InfraCAM* has individual pixel correction values that are programmed at the factory and require no additional recalculation in the field. This feature offers significant savings in space and power, as it obviates the requirement for an internal shutter or additional circuitry to acquire and calculate pixel correction coefficients. Therefore, there is no interruption in use while new coefficients are acquired. The block diagram of the highly efficient and concise video processing electronics is shown in figure 5.

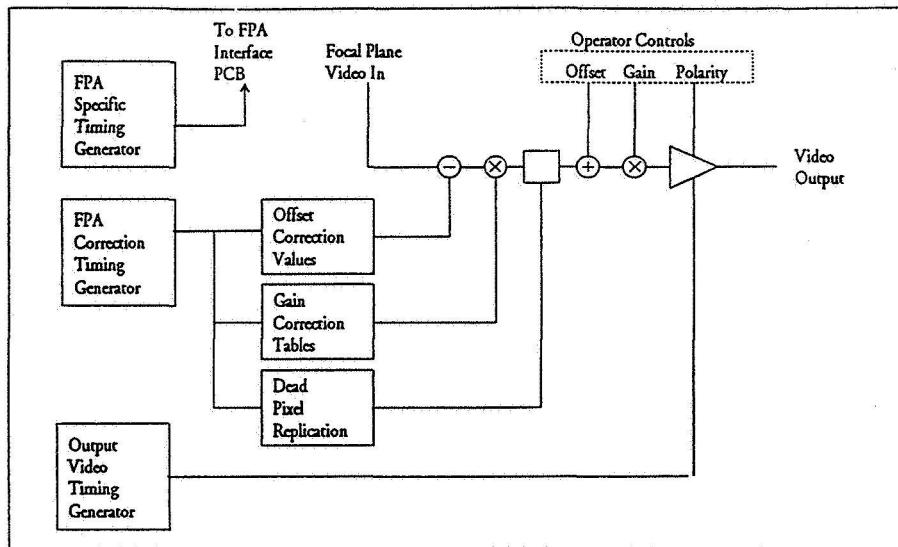


Figure 5: *InfraCAM* Video Processing Block Diagram

The patented Inframetrics microcooler is a critical component which permits the *InfraCAM* to meet the rigorous system requirements for size, weight and power. The palm-sized cooler measures 3.5" x 3.2" x 2.0" overall and weighs less than 0.66 pounds. Initial cooling of the detector is accomplished in less than seven minutes. A standby switch removes power from the video processor board, interface board and the viewfinder to conserve ~40% of the power, while maintaining the correct detector temperature. Video is instantly displayed when the unit is switched from standby mode into operating mode.

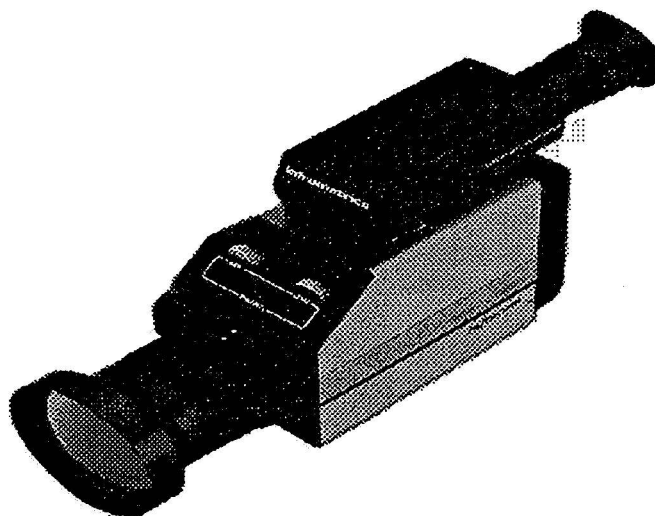


Figure 6: Commercial *InfraCAM*

7. INFRACAM MODIFICATIONS FOR DARTFIRE

In order to collect the required scientific data, the *InfraCAM* was specially modified. The modifications include: 1) the addition of a rotating filter assembly, synchronized to the frame rate, 2) extending the normal bandpass of the camera to 1.4 through 5.0 microns, 3) the addition of custom remote control circuitry, 4) a new close focus lens

design, 5) a new mechanical package, ruggedized to meet particularly demanding vibration environments and finally, 6) radiometric capability.

The small size of the original *InfraCAM* allowed the addition of an external filter wheel without violating the initial volume allocation within the experiment. It was decided that the filter wheel would be located behind the lens and just ahead of the dewar window. With the non-reimaging lens design, this provided for minimal size filters. The filter wheel contains six 1 inch diameter filters and rotates at a constant velocity of 60 RPM. The filter wheel is driven in a closed loop servo configuration by a DC gearhead motor. The final drive link is via an o-ring. The angular position of the filter wheel is identified by a combination of unique slots on the periphery of the wheel sensed by an optical sensor. The wheel is statically balanced.

The filter bandpasses were specified by the DARTFire science requirements. The filter properties are identified in table 2. Inframetrics chose to use the filter substrates to correct for focus shift (chromatic aberration) and to compress the temperature dynamic range. This allowed the scene to remain in focus without lens readjustment between filters. Additionally, the filter transmissions are limited by design to roughly equalize the signal on the detector (based upon the expected scene characteristics) for each filter.

Table 2: Filter Properties

<u>Filter No.</u>	<u>Bandpass (μm)</u>	<u>Bandwidth (μm)</u>	<u>Transmission (%)</u>	<u>Substrate</u>	<u>Thickness (inc)</u>
1	1.60	0.025	0.1	PK50	.27
2	1.87	0.100	3.9	PK50	.22
3	3.40	0.400	30.0	Silicon	.0628
4	3.80	0.025	2.6	Silicon	.0567
5	4.24	0.025	7.2	Silicon	.0507
6	4.80	0.100	71.0	Silicon	.0437

The DARTFire science requirements specified spectral data down to 1.6 microns. Since the commercial *InfraCAM* has a bandpass of 3.4 to 5.0 microns, a modification was necessary. This did not require the use of a different detector, since PtSi has very good responsivity down to 1 micron. Rather, Inframetrics elected to build the dewars with wide bandpass windows and wide bandpass coldfilters. In the final design the system *f*/# was increased to 2.5 to extend the temperature dynamic range of the instrument while still meeting sensitivity requirements. The new dewar optics, *f*/# and filter spectral transmission values were determined in a comprehensive system model generated by Inframetrics system engineers in conjunction with NASA LeRC scientists.

In order to change the camera settings while in orbit or during testing, the *InfraCAM* would require remote control capability. NASA engineers chose to have this capability implemented by ASCII codes from a PC via RS-232 link to the camera. All basic camera functions as well as the new filter status are controlled as shown in table 3.

Table 3: Remote Control Functions

<u>Function</u>	<u>Range</u>
Remote Control	Activate / Deactivate
Power	On / Off
Standby Mode	On / Off
Display Polarity	White Hot / Black Hot
Level	0-1023
Gain	0-1023
Filter Wheel Motor	On / Off
Motor Speed	0-1023
Go to Filter #	#1 - 6

To identify each filter a bar code was superimposed in one line of video at the top of each frame. The codes correspond to unobstructed video frames from each filter. These codes were generated by modification of the field-programmable gate array device within the *InfraCAM*. The remote control and the filter wheel drive was placed on a small double-sided surface mount technology circuit card mounted within the original *InfraCAM* package. The viewfinder was not used. On/off switches and battery terminals were brought out to external connectors. The addition of this circuitry altered the block diagram of the *InfraCAM* as shown in figure 7.

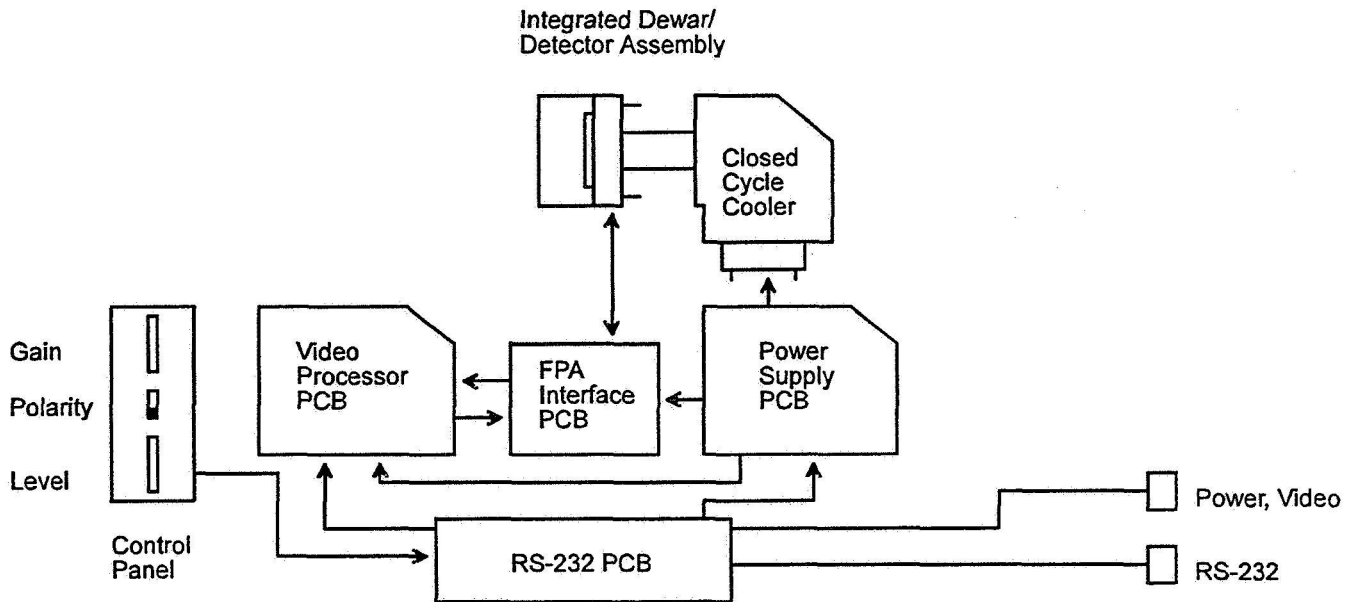


Figure 7: Block diagram of the modified *InfraCAM*

The burning PMMA is located approximately 18 inches from the *InfraCAM*. A new lens design was required due to close working range, the desired field-of-view, and the MTF specifications from NASA LeRC engineers. The lens requirements are satisfied with a single element anti reflection coated zinc selenide lens. The lens has 72 mm focal length lens. The random vibration environment is 19 g's RMS for 30 seconds over the frequency range from 10-2000hz.

Due to the addition of the external filter wheel and new lens a new mechanical package was designed consistent with space flight requirements. This package design meets the high random vibration environment expected during the mission. (See figure 8.)

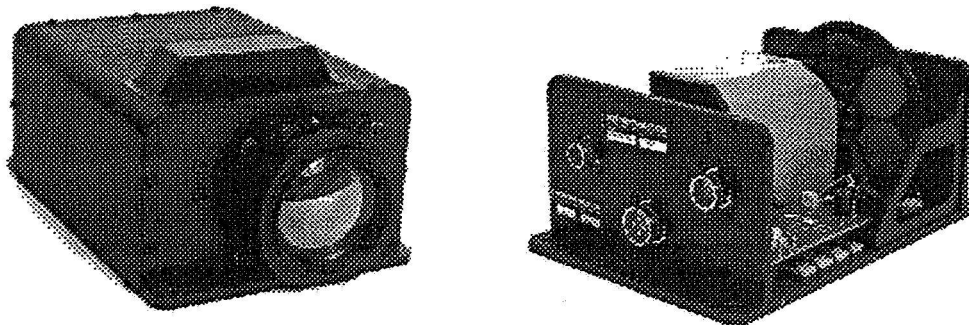


Figure 8: Modified *InfraCAM*

NASA LeRC specified that the data from the camera be fully radiometric. Inframetrics, a world leader in radiometric imaging systems, identified the hardware calibration and image processing steps necessary to implement radiometric capability in this imager. NASA LeRC engineers generated the image processing software to segregate the spectral band video data and yield radiometric data to the necessary accuracy. This was done in conjunction with Inframetrics engineers. Inframetrics empirically generated a response curve for each filter at different ambient conditions for use by NASA LeRC engineers in post processing. A typical response curve is shown in figure 9.

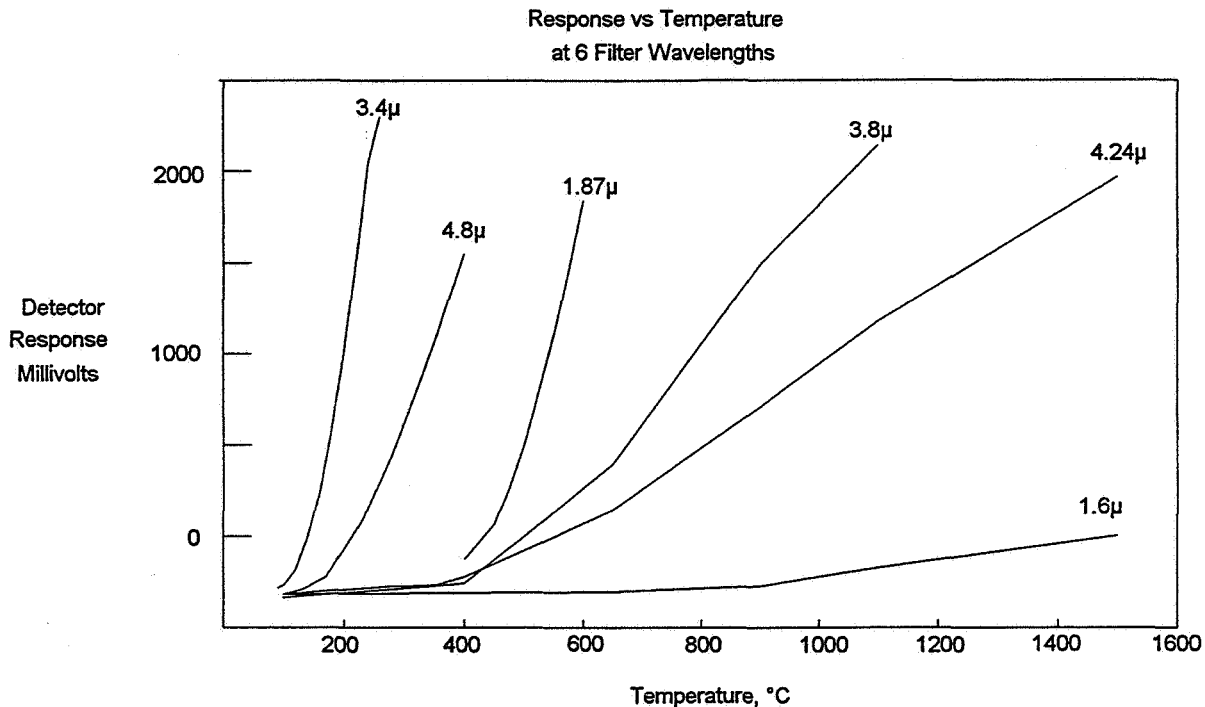


Figure 9: Typical Calibration Curve

8. HARDWARE INTEGRATION PROCESS

In the hardware integration process, critical components are breadboard tested in the laboratory prior to the procurement of flight hardware. The flight components undergo bench top performance testing and environmental screening before integration into the flight system. The environmental screening includes vibration testing to the sounding rocket launch environment and thermal cycle testing (environmental testing of the IR cameras was done by Inframetrics before delivery). The thermal cycle testing is intended to find components subject to premature failure, but was not required for the IR cameras because the NASA LeRC engineering team determined that testing would not establish an incrementally higher degree of reliability.

The components will be integrated into the two major subsections of the experiment: the optics subsection and the gas supply subsection. The subsections will be functionally tested before integration. The completed experiment package will be performance-tested on the ground and then further tested on the NASA LeRC DC-9 low gravity aircraft. These tests will be run as closely as possible to the mission configuration and sequence. Final verifications are performed on the flight-configured experiment package before shipment to WFF. At WFF, the experiment package is integrated to the remaining payload elements. The flight systems are verified, the payload is spin balanced, and the total payload is vibration tested. The payload is then shipped to WSMR for integration with the military surplus rocket motors. The rocket is mounted to the launch rail where the flow system oxidizer is

remotely loaded and final checkouts are performed. All experiment systems may be operated from the block house and all data and functions are monitored up to launch.

Figures 10, 11, and 12 are images from 1 G ground-based tests. The sample is PMMA with actual flight dimensions. The burn was performed in 35% oxygen concentration and 1 atm.

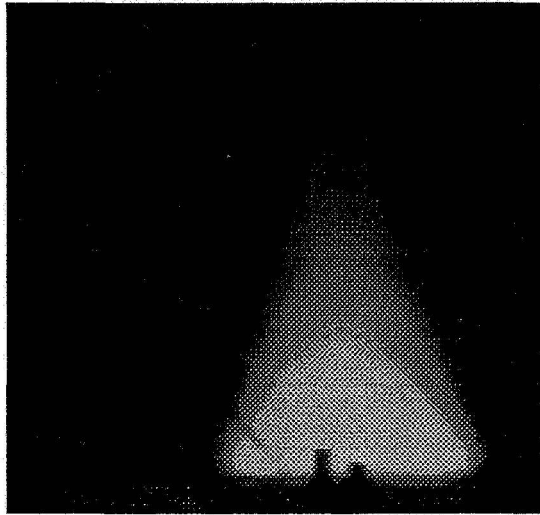


Figure 10: CO2 emission of PMMA 4250 nm

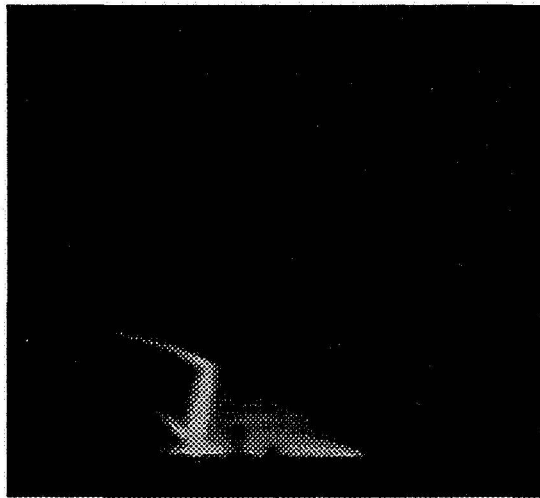


Figure 11: MMA emission of the PMMA 3399 nm

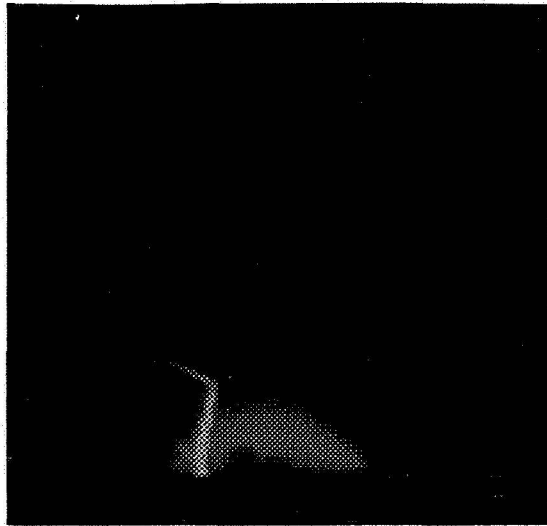


Figure 12: CO emission of the PMMA 4803 nm

The experiment is scheduled for three flights. The flights are scheduled for September 1995, March 1996 and October 1996. The six months between flights will provide time for the principal investigator to analyze the flight data and recommend adjustments to the test matrix for the next flight.

9. PLANNED DATA POST PROCESSING

Each flight will produce two videocassette tape of images from the IR camera and the UV/visible camera. All the flight images will be digitized and stored on random accessed magnetic and optical storage media that is accessible by a workstation for further processing. The bar code of each image is read and images are synchronized with the filter wheel and sorted into six sequences of images. Each image is linked to its corresponding flight digital data that contains the reading from the experiment sensors. The left and right halves of each image of different flames will be separated into two images and annotated with all the flight data. Each image will be processed for various scientific needs.

10. CONCLUSIONS

The complex requirements for a spaceborne IR camera, specifically configured to meet the needs of the DARTFire experiment have been satisfied via modification of the commercially available *InfraCAM* at a fraction of the cost of the design of a custom camera. The small size and low power of the *InfraCAM* provided a distinct advantage for conversion to a dual use sensor. Data obtained by the *InfraCAM* in the DARTFire experiment shall expand basic scientific knowledge regarding the physics of flame propagation for the purpose of fire safety on earth and in space.

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